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MANNED CERTIFICATION EVALUATION OF THE INNERSPACE SYSTEMS® MEGALODON UNDERWATER BREATHING APPARATUS

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The Megalodon underwater breathing apparatus (UBA) was used in completing 99 man-dives. The primary test objective was to determine whether the UBA could control oxygen sufficiently to satisfy performance specifications published by Naval Surface Warfare Center Panama City (NSWC-PCD).

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19. ABSTRACT (continued)

The UBA failed in 4.9% of the 61 dives analyzed. One failure was due to PO_2 overshoot duration greater than the allowed three minutes; two were due to regulation of post-overshoot PO_2 >1.45. The UBA's performance adequately met the predetermined reject rule of <15% failure rate at 95% confidence. When used in conjunction with MK 16 MOD 1 dive tables, the Megalodon is deemed to meet NSWC-PCD performance specifications for N_2-O_2 dives up to 190 feet and He-O_2 dives up to 300 feet. When diving, Megalodon users must maintain adequate training and familiarity with the apparatus.

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The investigators thank everyone at NEDU who made this study possible: the divers who exposed themselves to the risks associated with underwater work; the control room watches and special warfare locker personnel who made the dives happen; and the medical deck and instrumentation personnel who did an outstanding job. Special thanks to Dr. Wayne Gerth for his counsel and advice, and also to Rick Steckel and Ken Markee for conducting the benchtop experiments in Appendix C — and to Task Leader NDC Chuck Blanchard, who made this project a success.

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INTRODUCTION

The InnerSpace Systems® Megalodon is a closed-circuit, mixed-gas underwater breathing apparatus (UBA). In a UBA of this type, the diver's expired gas is circulated through counterlungs and a CO_2 absorbent canister and rebreathed. Oxygen partial pressure (PO_2) in the breathing circuit is monitored, and oxygen is added if the PO_2 decreases below a set point. Diluent gas, a mixture of oxygen and nitrogen or helium, is added to maintain the volume of the breathing circuit. As a result, gas use is efficient, and diver-inspired gas has a relatively constant PO_2 irrespective of depth.

For some operational scenarios the Megalodon may be a cost-effective alternative to the MK 16, the only closed-circuit, mixed gas, self-contained UBA currently authorized for Navy use. The Megalodon differs from the MK 16 in several key features. The Megalodon uses counterlungs that are located over the shoulders with some latitude for user adjustment. This configuration positions the counterlungs level with the lung centroid and consequently minimizes the hydrostatic lung load for a diver in a horizontal swimming position. The Megalodon has several user-selectable PO_2 set points, ranging from 0.4 to 1.4 atmospheres (atm) that can be changed during the dive. It also has a modular design that enables it to be configured with different-sized CO_2 absorbent canisters and flasks for diluent and oxygen. The configuration tested by the U.S. Navy used off-the-shelf k-bottles for diluent and oxygen flasks, which have larger capacities than those of the MK 16 MOD 1. The Megalodon UBA tested by the U.S. Navy differed from the commercially available UBA by having aluminum-fabricated components in place of the Delrin® ones in the commercial model.

The Megalodon compares favorably to the MK 16 MOD 1 in respect to PO_2 control, work of breathing, and canister duration in unmanned testing.[1] In accordance with Naval Sea Systems (NAVSEA) 00C Task Assignment 10-09 (June 2010), Navy Experimental Diving Unit (NEDU) performed manned testing of the Megalodon to determine its suitability for certification to 190 feet of seawater (fsw) with nitrogen-oxygen (N_2-O_2) and to 300 fsw with helium-oxygen (He-O_2) diluents.

METHODS

The general testing philosophy was to continuously measure PO_2 in the inhalation hose (inspired PO_2) of the Megalodon during "hands-off" manned diving: i.e., divers breathed the UBA but did not manually add oxygen. Automatic control of the inspired PO_2 set point was evaluated during changes in ambient pressure, breathing loop volume variations, incidental gas loss such as during mask clearing or leaks, and variations in diver oxygen consumption with work rate.

Before each diving day, the five UBAs tested in this study were calibrated and prepared in accordance with the Megalodon reference manual.[2] The diluent flask was charged with either 79% N_2-21% O_2 or 88% He-12% O_2. For oxygen control testing (Part I), the Megalodons were each fitted with a T-bit, and divers used a half face mask. For form, fit, and function testing (Part II), two Megalodons were fitted with the KMS 48 full face

mask and two with the MK 24 full face mask. The only modification to each Megalodon configuration was a sensor block fitted in line between the T-piece (just off the inhalation counterlung) and the inhalation hose. The sensor block had an unobstructed straight flow path 9 cm in length and 2.8 cm in internal diameter (similar to the inhalation hose), with a total volume of approximately 1.839 in^3 (0.03 L). This flow path constituted only a minute fraction of the Megalodon's ~11 L breathing loop volume. A side port of the sensor block housed a K-1D oxygen sensor and amplifier assembly exposed to, but not obstructing, gas flow to the inhalation hose.

DIVING PROCEDURES

Manned diving was approved by the NEDU Institutional Review Board. All test divers recruited as volunteers by the task leader were military-trained divers. Before the Ocean Simulation Facility (OSF) test dives, each diver was familiarized with the basic operation of the Megalodon in the NEDU Test Pool via NEDU Short Form Test Plan 10-24.[3] A maximum of four divers participated in each OSF test dive. Divers dressed for thermal comfort ranging from swimsuits and t-shirts to wet suit; one diver wore a dry suit for Part II dives.

Eight dive profiles were tested: five single dive profiles using N_2-O_2 diluent to different depths including the maximum certification depth of 190 fsw, and three single dive profiles using He-O_2 diluent to different depths including the maximum certification depth of 300 fsw. All dives required decompression stops. Dive profiles are listed in Appendix A; most pertinent to oxygen control, they covered a range of bottom times, maximum depths, and first decompression stop depths. Within a week before making the 300 fsw He-O_2 dive, divers performed at least one shallower workup dive.

Part I: Oxygen Control

Four hysteresis-braked (HB210, Magtrol; Buffalo, NY) underwater cycle ergometers were staged on the OSF wet pot high stand. These custom-built ergometers replace the no longer available Collins (Braintree, MA) ergometers. These ergometers are constructed so that divers pedal in a semiprone position (with an ~45° head-up inclination). Water temperature was controlled and ranged from 80 to 84 °F. The OSF was compressed with air for all dives. A MK 16 MOD 1 UBA charged with the same diluent as the Megalodon UBAs served as an emergency breathing system, and four surface-supplied open circuit regulators provided an emergency gas supply. Although divers could stand and breathe chamber air in the event of an emergency, a diver breathing from the emergency breathing system or emergency gas supply could be decompressed on the same or only slightly modified schedules as divers remaining on the Megalodon.

All diving operations were conducted in accordance with standard Navy diving procedures[4] except for the following. Test divers were not to manually add oxygen to their UBA breathing loops unless their secondary displays showed a PO_2 level <0.4 atm — or unless they were instructed to do so by the dive watch officer or the dive watch

supervisor. Test divers were also discouraged from manually adding diluent to their UBA breathing loops, but diluent was added if it was necessary to do so.

The OSF was then compressed at a target descent rate of 60 fsw/min. Descent was interrupted at 33 fsw while divers manually adjusted their UBA PO_2 set points from 0.7 to 1.3 atm. The divers were verbally prompted through the required series of button pushes to ensure transition of set point at the same time and to minimize the delay between UBA transition and continuation of descent. This procedure typically took 20 s, with a further delay of 5 s between confirming the 1.3 atm set point and resuming descent at a target rate of 60 fsw/min to the maximum depth. This procedure was intended to minimize delay at 33 fsw so that Megalodon dives were as comparable as possible to previous MK 16 MOD 1 dives,[5,6] in which descents were not interrupted because the MK 16 MOD 1 oxygen set point transitions automatically to 1.3 atm on descent through 33 fsw.

Within one minute of arrival at bottom, divers began continuous ergometer work. For one dive profile, they worked for 50 minutes, rested for 20, and then resumed work for 20 more minutes. They pedaled at a target cadence of 60 revolutions per minute and a dry work rate of 35 W set on the ergometer controller (W.E. Collins; Braintree, MA). From the added resistance of water, these figures equate to an actual power of 105 W and a diver oxygen consumption of 1.9 L/min for divers wearing swim-suits and t-shirts or wet suits.[7,8]

Five minutes before the end of the planned bottom time, divers stopped ergometer work and assumed a relaxed position on their ergometers. At the completion of bottom time, the OSF was decompressed according to the appropriate MK 16 MOD 1 decompression schedule (Appendix A), with a target ascent rate of 30 fsw/min to and between stops. The final ascent to the surface was interrupted at 12 fsw while divers manually adjusted their PO_2 set points from 1.3 to 0.7 atm.

Generally, two N_2-O_2 dives using the same UBAs but different dive teams were conducted each day. Often the absorbent canister and gas flasks were replenished between such same-day repeat dives, but one same-day repeat dive series was conducted with no such UBA maintenance between dives. In this series, the same four UBAs were dived twice with a two-hour surface interval, during which the electronics package of two UBAs remained energized and two were turned off and then turned back on.

Part II: Form, Fit, and Function

Part II diving was similar to Part I with the following exceptions. Divers wore full face masks. Descent rate was a maximum of 60 fsw/min and was generally slower. Underwater work was operational in nature, and the required equipment was located on the OSF deck. Four tasks were each performed for ten minutes. The four tasks were (1) walking on an underwater treadmill while carrying a solid cast iron kettlebell that weighed 53 lb (24 kg) when not immersed; (2) lifting a 53 lb kettlebell from the deck 36 inches (100cm) to a bench, and then another 18 inches to a higher bench, and then

lowering it in reverse sequence; (3) kneeling on a bench 24 inches (60 cm) high and lifting a 53 lb kettlebell from the deck to the bench and back; and (4) completing a manual dexterity project requiring assembly of a pipe flange with nuts and bolts.

INSPIRED PO_2 MEASUREMENT

PO_2 was measured with a K-1D (Teledyne; Thousand Oaks, CA) microfuel cell oxygen sensor housed in a sensor block located in line between the inspiration counterlung and the inspiration hose. Although 13 inches (33 cm) upstream from the mouth, this location was assumed to be representative of inspired gas. The K-1D voltage signal was amplified approximately fiftyfold with an amplifier integrated into the sensor housing. Before each dive, a two-point calibration was performed by recording sensor voltage while flushing each sensor assembly (microfuel cell, amplifier, and housing) with 100% nitrogen and then 100% oxygen at 1 atm·abs. Calculated PO_2 and work rates for each diver, along with wet pot pressure in fsw and water temperature, were acquired at 1 Hz to a microcomputer-based data acquisition system.

PO_2 readings on the UBA secondary displays were compared to the data acquisition PO_2 readings upon reaching bottom, again just before leaving bottom, and at several times during decompression stops.

ANALYSIS OF DEPTH, TIME, AND INSPIRED PO_2 RECORDINGS

Maximum depth, bottom time, ascent rate to the first stop, first stop average depth, and first stop duration were extracted from the recorded pressure-time profile. Since a delay always occurred at 33 fsw, the descent rate was calculated from leaving that 33 fsw PO_2 set point depth to reaching the maximum depth. The following metrics were calculated from each UBA inspired PO_2–time recording (see Figure 1 for some of these metrics). During descent, breathing loop PO_2 increased and could overshoot the set point. The overshoot was defined as the period during which PO_2 exceeded 1.45 atm. Overshoot duration and time-weighted average (TWA) PO_2 during overshoot were calculated for this period. Overshoot was considered to have ended when PO_2 became $\leq$1.45 atm and subsequently remained $\leq$1.45 atm for more than 30 seconds (see Figure 1). The central nervous system toxic dose excess (CNSTDE), an overshoot metric, is defined as those positive values of:

$$\text{CNSTDE} = (\text{inspired}\,PO_2 - 1)^{3.4} - 0.0167\,. \qquad (1)$$

The power function is based on the CNS toxicity model of Harabin et al.[9] The rectangular approximation to the integral of the CNSTDE was taken during the period of overshoot. Maximum PO_2 obtained at any time was also recorded.

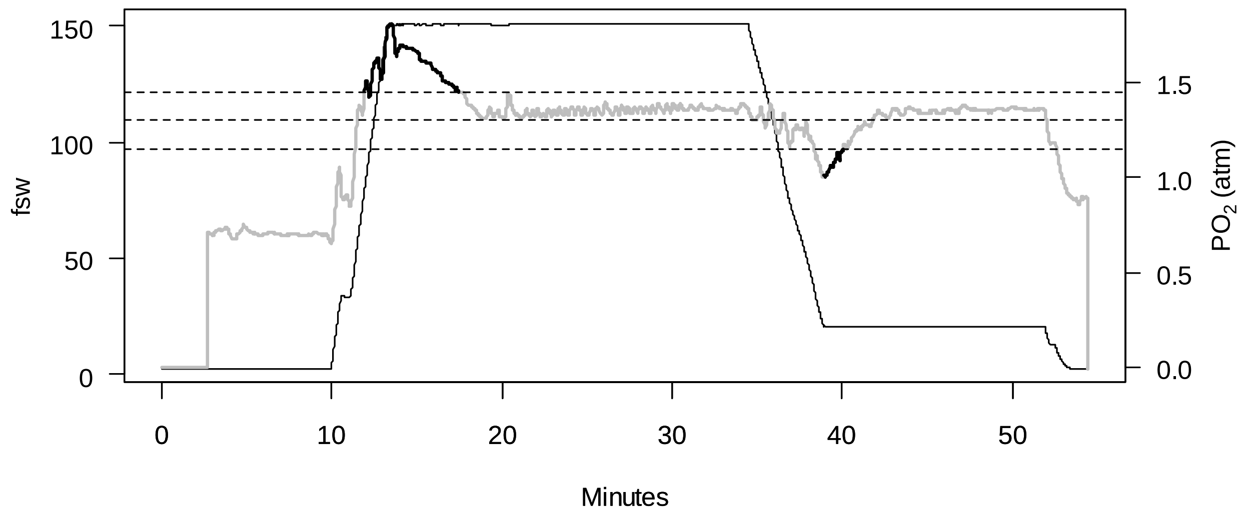

Figure 1. Profile of a 150 fsw N_2-O_2 dive. The depth profile (thin black line) shows the pause at 33 fsw during descent and 12 fsw during ascent for manual transition between the 0.7 atm and 1.3 atm PO_2 set points. The grey line is the measurement of inspired PO_2, and the heavy black segments illustrate the overshoot and undershoot. Horizontal dashed lines indicate the PO_2 set point of 1.3 atm, and the acceptable control band (1.15 – 1.45 atm).

General control of the PO_2 set point was embodied in the TWA PO_2 calculated for several time periods: for the entire bottom time, the portion of bottom time after the overshoot ended, and the entire dive.

During ascent, breathing loop PO_2 decreases and can undershoot the set point. The undershoot is greatest with a long, uninterrupted ascent and was therefore evaluated only upon arrival at the first decompression stop. The undershoot period was defined as that from reaching the first decompression stop until the first time PO_2 became ≥1.15 atm and subsequently remained ≥1.15 atm for more than 30 seconds, or until the end of the decompression stop. Minimum PO_2 and TWA PO_2 for the ascent were calculated for the period from leaving the bottom to reaching the surface.

Integral CNSTDE was expressed in units of atmosphere seconds (atm·s); all times are expressed in minutes, all depths in fsw, and all PO_2s in atm.

EXPERIMENTAL DESIGN

Each UBA-dive was evaluated as a pass or fail on the basis of the criteria adopted from the Naval Surface Warfare Center (Panama City) UBA oxygen control performance specification. A UBA-dive failed due to:

1. a minimum inspired PO_2 <0.40 atm at any time;
2. an undershoot duration longer than four minutes;

3. an integral CNSTDE ≥360 atm·s;
4. a post-overshoot TWA PO_2 >1.45 atm or <1.15 atm; or
5. a UBA malfunction not attributable to improper maintenance, setup, or operation.

Pass/fail criteria 1–4 were based solely on the K-1D oxygen sensor data. Readings periodically taken from the secondary display of the UBA's onboard oxygen sensors during the dive were not used for this purpose.

<u>Primary Outcome — UBA Failure</u>

The performance specification defines failure of UBA oxygen control but does not specify the allowable rate of these failures. The allowed failure rate (no more than 15%) used in this trial was selected to ensure an oxygen control performance equal to or better than that of the MK 16 MOD 1, a closed-circuit, mixed gas UBA already authorized for Navy use. Testing was to be terminated and a recommendation issued against accepting the Megalodon if its failure rates exceeded those shown in Table 1 (stop-high). A recommendation to accept the Megalodon UBA would result from an early stop-low or from completion of all dives without a stop-high. Binomial outcome numerical error rate simulations (Figures 3 and 4) indicated that this design would result in an approximately 5% probability of accepting the Megalodon if it had an actual failure rate >15% or an approximately 7% probability of rejecting the UBA if it had an actual failure rate <15% (Table 2).

Table 1. Binomial trial stopping rules

Stop-high if 85% confident >15%		Stop-low if 85% confident <15%	
Number of failures or more	Number of dives or fewer	Number of failures or fewer	Number of dives or more
3	9	0	12
4	14	1	22
5	19	2	31
6	24	3	39
7	29	4	47
8	35	5	55
9	40		
10	46		
11	52		
12	57		
13	60*		

* imposed by maximum trial size

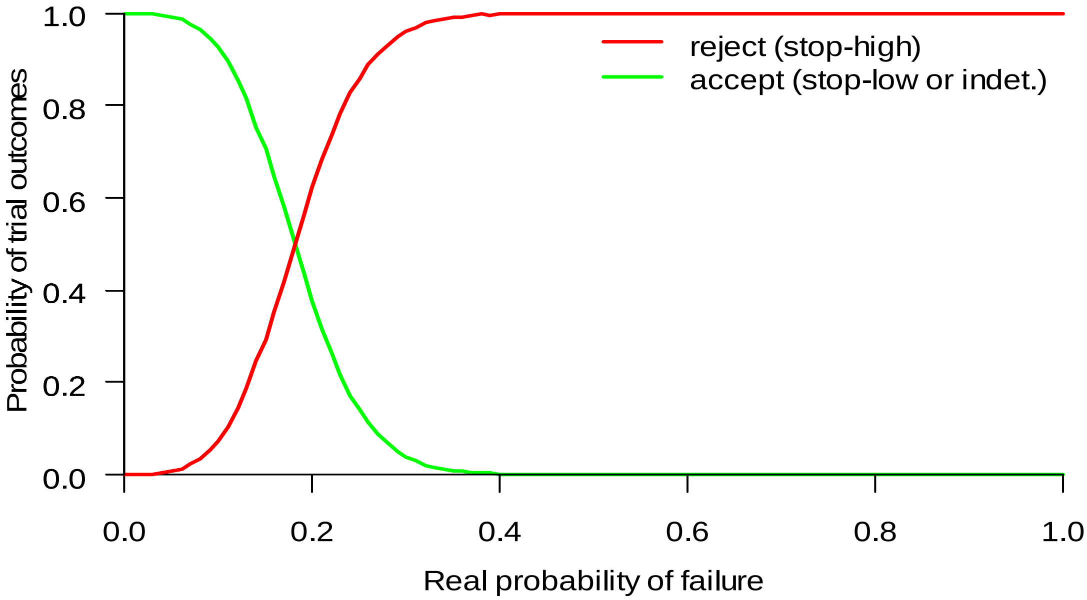

Figure 2. Probability distributions of possible outcomes for the trial design given in Table 1, with maximum trial size n=60. Estimated probabilities of trial outcomes (y-axis) are the relative frequencies from 10,000 trial simulations at each selected value of the real probability of failure (x-axis). Accepting the UBA results from either reaching a stop-low or the "indeterminate" (indet.) outcome of completing 60 dives without a stop-high or stop-low.

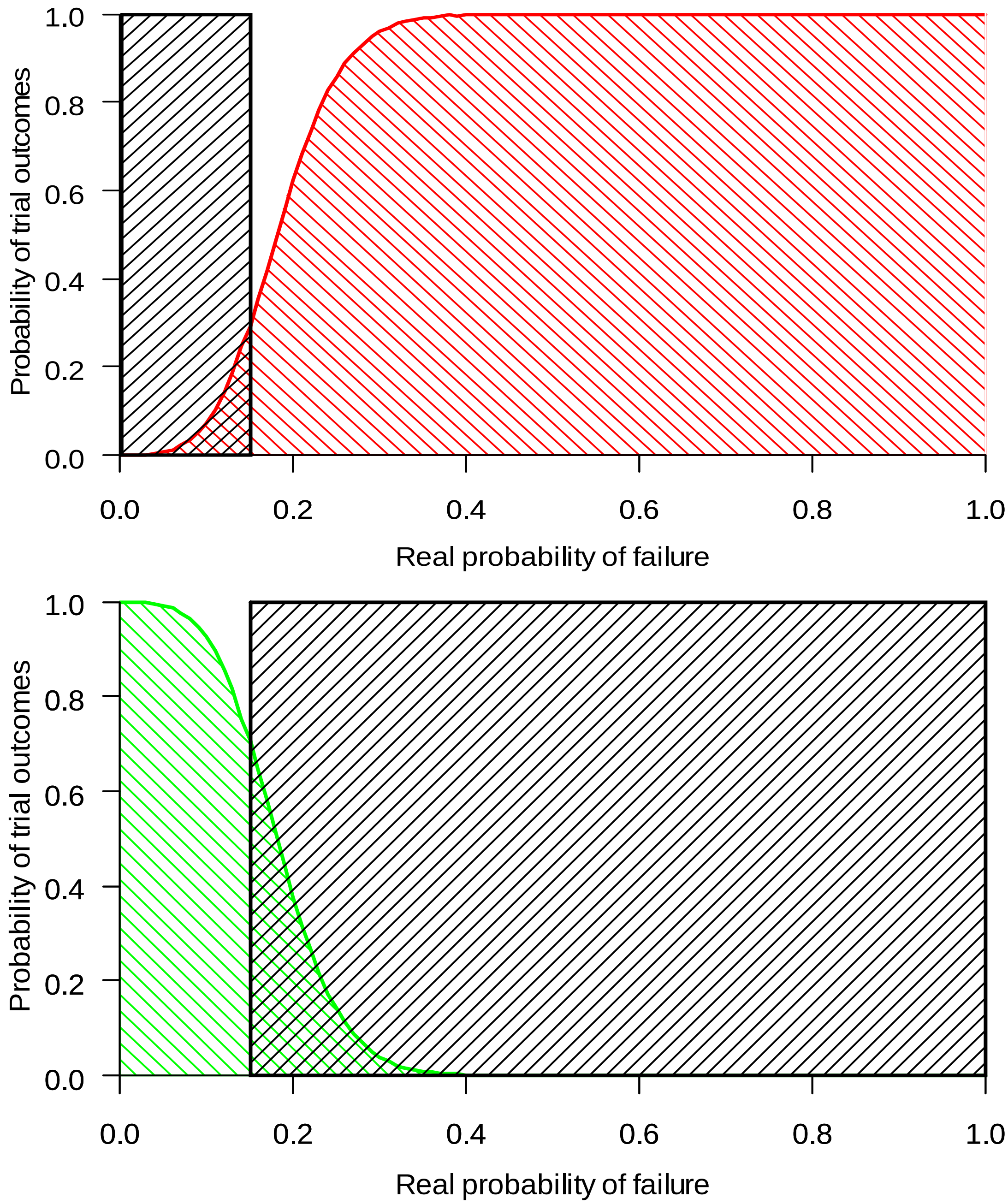

Figure 3. Top panel: The conditional probability of a reject trial outcome (stop-high), if the real probability of UBA failure is <15%. The area inside the rectangle is the probability of all possible trial outcomes for a real probability of failure <15% [*P*(A), 15%]. The area under the reject distribution is the probability of a stop-high trial outcome for all real probabilities of failure [*P*(B)]. The intersection of these two areas (cross-hatching) is the probability of a stop-high trial outcome for real probabilities of failure <15% [$P(A \cap B)$]. The conditional probability of a stop-high trial outcome, if the real probability of failure <15% [$P(B|A)$], is the cross-hatched area divided by the rectangular hatched area [$P(A \cap B)/P(A)$], a value given in Table 2 as "Reject error rate." Bottom panel: The conditional probability of an accept trial outcome (stop-low or indeterminant), if the real probability of failure is >15%, is the cross-hatched area divided by the rectangular hatched area, a value given as "Accept error rate" in Table 2.

Table 2. Probability of various trial outcomes

$P_{rej\|acc}$=T	$P_{acc\|acc}$=T	$P_{indet\|acc}$=T	$P_{rej\|rej}$=T	$P_{acc\|rej}$=T	$P_{indet\|rej}$=T	Reject error rate	Accept error rate
0.0691	0.7569	0.1740	0.9472	0.0176	0.0352	0.0691	0.0528

Secondary Outcome — Direct Comparison with MK 16 MOD 1

The same PO_2 control metrics were calculated from inspired PO_2-time recordings from previous NEDU MK 16 MOD 1 dives[5,6] and were selected for depths and diluent gases matching those of the present dive profiles. T-tests were used to compare relevant metrics for matched dives between the Megalodon and MK 16 MOD 1.

All data analysis was conducted using “R: A language and environment for statistical computing” (R Development Core Team, Version 2.8.0; Vienna [Austria]: The R Foundation for Statistical Computing, 2008. URL http://www.R-project.org).

QUALITATIVE ASSESSMENT OF THE MEGALODON

After each dive, divers were asked to complete an anonymous questionnaire subjectively evaluating aspects of Megalodon performance. A maintenance log was kept for each Megalodon.

RESULTS

GENERAL DIVING

Table 3 shows the number of divers on each of the five Megalodons. A total of 99 UBA-dives were conducted, but only 61 were analyzed for oxygen control failure rate. Partial data losses resulting from instrumentation problems occurred late in two UBA-dives but did not critically affect data analysis and therefore were included. Of the 61 UBA-dives used in oxygen control analysis, 47 were N_2-O_2 and 14 were He-O_2 dives.

Table 3. Number of dives per Megalodon

UBA#	N_2-O_2 dives	He-O_2 dives	Total
1	17	6	23
2	3	0	3
3	18	5	23
4	20	6	26
5	20	4	24

The dives excluded from oxygen control analysis included the 14 for form, fit, and function dives conducted in Part II, because work rate was not characterized. In Part I, eight UBA-dives were aborted and could not be used for data analysis. In one instance, a diver incorrectly transitioned his UBA to manual mode, and all four divers were

brought to the surface. In another instance, a diver added oxygen instead of diluent on descent, and all four divers were also brought to the surface. Neither of these aborts resulted from UBA malfunction, and were not considered UBA-dive failures. The initial 16 dives were excluded from failure rate analysis because they were conducted with the K-1D oxygen sensor assembly placed upstream from the inspiration counterlung. Since considerable gas mixing occurs in the counterlung, this upstream sensor assembly position may not have been representative of inspired gas.

Among these 16 dives with the oxygen sensor inappropriately located, four are worth noting. In addition to the standard descent with a brief pause at 33 fsw, another descent procedure was originally planned for testing. In this procedure, divers were to transition their UBAs at 20 fsw and remain at this depth until UBA PO_2 stabilized at 1.3 atm before descent continued to 130 fsw. This procedure was designed to mimic use of closed-circuit, mixed gas UBAs for multiple downward excursions from a shallow depth with a 1.3 PO_2 set point. One four-man dive was attempted, and it was aborted when UBA PO_2 exceeded 2.0 atm for five minutes. This procedure was deemed unsafe and was not repeated, so it was never characterized with the sensor assembly downstream of the counterlung.

Divers were instructed to refrain from manually adding diluent to the breathing loop during descent, unless doing so was absolutely necessary. Early in testing, divers repeatedly criticized the Megalodon's automatic diluent addition as being insufficient to maintain an adequate breathing loop volume during descent. After this criticism arose, a record was kept of how many manual additions divers needed to perform during descent. Data were collected from 65 UBA-dives, 49 of which required manual diluent to be added. The mean number of additions was three per man-dive. Table 4 summarizes these data.

Table 4. Manual diluent additions during descent

Number of Manual Diluent Additions	Number of UBA-dives	Number of Manual Diluent Additions	Number of UBA-dives
0	16	4	12
1	7	5	11
2	4	7	4
3	10	10	1

GENERAL OXYGEN CONTROL

Table 5. Time-weighted average (TWA) PO_2, all analyzed dives (n=61)

	TWA PO_2 Bottom Time	TWA PO_2 post-OS	TWA PO_2 dive
Min	1.35	1.33	1.32
Median	1.41	1.38	1.37
Mean	1.43	1.39	1.37
Max	1.61	1.46	1.47
NA		3	

NA due to 3 dives to 80 fsw with no overshoot (OS)

Table 5 illustrates overall control of PO_2. The TWA PO_2 for the entire bottom time (TWA PO_2 Bottom Time) was greater than the 1.3 atm set point and heavily influenced by the overshoot, which generally comprised a substantial portion of the mostly short bottom times in this study. The TWA PO_2 post-overshoot (TWA PO_2 post-OS) and the TWA PO_2 for the entire dive (TWA PO_2 dive), which are less influenced by the overshoot, were only slightly greater than the set point.

Only three of the 61 UBA-dives failed the performance specifications, all as a result of elevated PO_2, giving a failure rate of 1 to 14% (95% confidence limits) A stop-low criterion was reached after 40 UBA-dives had been completed, but at this point no He-O_2 dives had been conducted, so the trial was continued to test the UBA with He-O_2 diluent.

Megalodon Primary Display Readings

Divers reported the Megalodon primary display PO_2 upon reaching bottom, before they began ascending, and during some decompression stops. The PO_2 upon reaching bottom was typically changing rapidly and it was therefore difficult to match the primary display reading to the independent, K-1D measurements. However, PO_2 levels at the other report times were relatively stable and those readings were compiled and found to have a mean of 1.30 (SD 0.02, n=193), indicating that the UBAs were controlling PO_2 in accord with their internal sensors. The mismatch between these internal sensors and the independent measurements (see Table 5) is discussed in Appendix C:.

UBA FAILURES

Overshoot

PO_2 overshoot (Table 6) during descent was generally not severe. One dive failed due to overshoot: it exceeded the integral CNSTDE threshold of 360 units as well as having TWA PO_2 post-overshoot >1.45 atm (see Table 7).

Table 6. Overshoot data, all dives (n=61)

	Descent rate	Max PO_2	OS duration	TWA PO_2 OS	Integral CNSTDE
Min	53.10	1.46	0.52	1.48	2.12
Median	56.99	1.81	5.54	1.63	75.70
Mean	57.61	1.80	5.95	1.63	10.52
Max	63.93	2.24	12.03	1.83	495.17
NA			3	3	3

NA due to 3 dives to 80 fsw with no overshoot (OS). TWA PO_2 OS: TWA PO_2 during overshoot

Table 7. Dives with maximum inspired PO_2 >2 atm

Descent rate	Max Depth	Diluent	Max PO_2	Time exceeding 2 atm	OS duration	TWA PO_2 OS	Integral CNSTDE
54.66	191.00	N	2.01	0.05	8.37	1.73	196.97
55.09	191.12	N	2.24	3.30	12.03	1.83	495.17
55.09	191.12	N	2.05	1.38	11.57	1.76	318.00
55.09	191.12	N	2.02	0.12	7.93	1.75	211.31
55.09	191.12	N	2.14	1.72	8.75	1.79	287.31
53.10	300.91	He	2.01	0.15	8.50	1.73	196.39
53.93	302.38	He	2.07	0.57	11.20	1.76	312.52

OS: overshoot; TWA PO_2 OS: TWA PO_2 during overshoot

Maximum inspired PO_2 (Max PO_2) exceeded 2.0 atm on only seven dives (Table 7). These high PO_2s were accompanied by long overshoot durations and seven of twelve of the highest integral CNSTDEs. No CNS toxicity events were reported.

Post-overshoot TWA PO_2

Two UBA-dives failed due to TWA PO_2 post-overshoot being >1.45 atm. These two failures and the one combined TWA PO_2 post-overshoot and CNSTDE failure just described all occurred on the same OSF dive to 190 fsw for 25 minutes bottom time, with a descent rate of 55.09 fsw/min (see Table 7).

UNDERSHOOT

No failures resulted from prolonged undershoot (see Table 8). For some UBA-dives, TWA PO_2 during ascent was less than 1.3 atm. Table 9 shows that TWA PO_2 during ascent <1.3 atm was associated with short total ascent time. These were dives to depths between 80 and 150 fsw maximum depths with only a 20 fsw decompression stop, and travel times during ascent ranged from 3.48 to 6.17 minutes. For these dives, low PO_2 during ascent, along with the transition to a 0.7 atm set point at 12 fsw on ascent, contributed substantially to the TWA PO_2 during ascent.

Table 8. PO_2 during ascent for all dives with first stop of at least 4 min duration (n=49)

	Ascent rate	US duration	Min PO_2 ascent	TWA PO_2 ascent
Min	26.93	0.00	0.88	1.23
Median	28.68	1.02	0.92	1.30
Mean	28.55	0.87	0.92	1.30
Max	29.44	1.82	1.00	1.37

US: undershoot

Table 9. PO_2 during ascent for all dives with TWA PO_2 during ascent <1.3 atm (n=22)

	Ascent rate (fsw/min)	US duration	Min PO_2 ascent	TWA PO_2 ascent	First Stop duration	Total Ascent Time
Min	26.93	0.53	0.88	1.23	6.93	10.41
Median	28.70	1.28	0.91	1.28	9.92	15.10
Mean	28.53	1.25	0.91	1.27	9.76	14.84
Max	29.18	1.82	0.96	1.29	12.92	19.09

US: undershoot

OXYGEN CONTROL DURING REPEAT DIVES

Two N_2-O_2 dives were routinely performed each day with the same UBAs (but with different divers). Often the CO_2 absorbent was replaced and the gas flasks refilled, but no other maintenance was performed. On one day, four UBAs were dived twice (a total of eight UBA-dives) with no maintenance performed during the surface interval. The primary electronics of two UBAs were left on during the two-hour surface interval. For the other two UBAs, the primary electronics were turned off at the beginning of the surface interval and then turned back on prior to the second dive. These repeat dives confirmed that oxygen control was maintained following a surface interval, regardless of whether the UBA oxygen control electronics package had been left energized or not.

However, during the second dives each day, irrespective of the maintenance performed during the surface interval, the Megalodons controlled PO_2 at levels higher than in the first dives. TWA PO_2 post-overshoot and TWA PO_2 for the entire dive were compared for the 16 pairs of same-day repeat UBA-dives. These PO_2 control metrics were chosen for comparison because they define general PO_2 control and are least influenced by diver metabolism (these repeat UBA-dives were conducted by different divers). Same-day repeat UBA-dives followed the same dive profile. The TWA PO_2 post-overshoot was significantly higher during second dives (1.43; SD 0.02 atm) than during first dives (1.38; SD 0.01 atm, 2-sided, paired t-test; $p<0.0001$). Similarly, the TWA PO_2 dive was significantly higher in repeat dives (1.40, SD 0.04 atm) than in first dives (1.36; SD 0.02 atm, 2-sided, paired t-test; $p<0.0001$). Indeed, all three of the UBA-dive failures, all due to high PO_2, occurred on the second dive of the day.

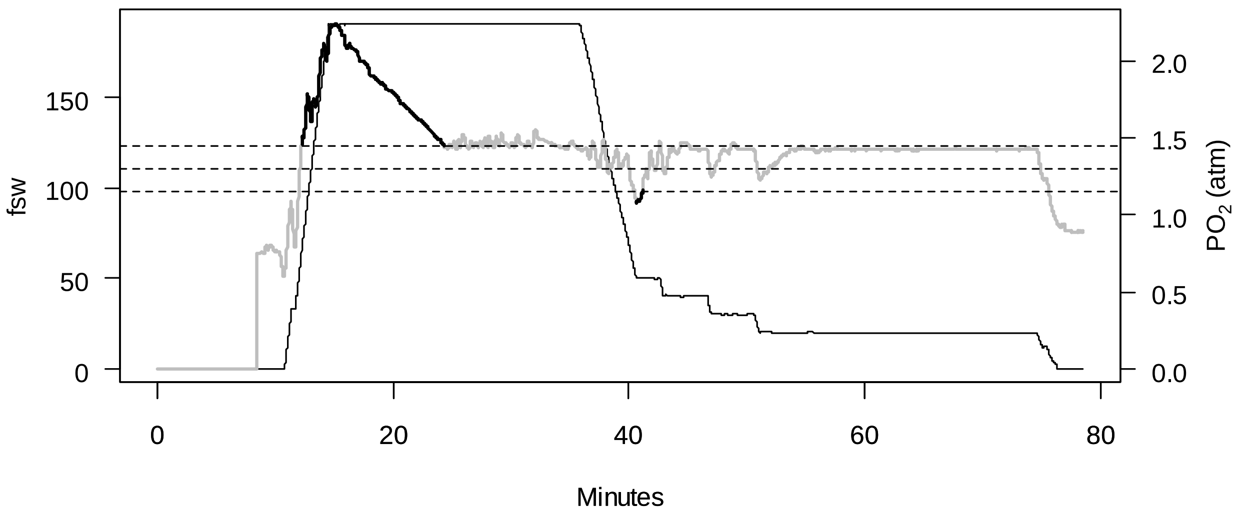

Figure 4. A second-dive-of-the-day profile (illustrated as in Figure 1), showing one of the UBA-dive failures. Note the large overshoot (first heavy black segment) and then the UBA's failure to control postovershoot PO_2 within the defined control band (outer horizontal dashed lines).

The higher PO_2s during same-day repeat dives probably resulted not from the repeat nature of the dive but from total duration of diving on that day. A likely culprit is moisture accumulation on the oxygen sensors in the Megalodon control loop (see Appendix C). Most of the test dives had relatively short (20–30 min) bottom times, so to verify that PO_2 would not continue to increase during longer bottom times, a previously unplanned profile to 80 fsw for 95 min was conducted. Figure 5 illustrates that the inspired PO_2 during this dive reached a plateau at approximately the value seen in those shorter dives.

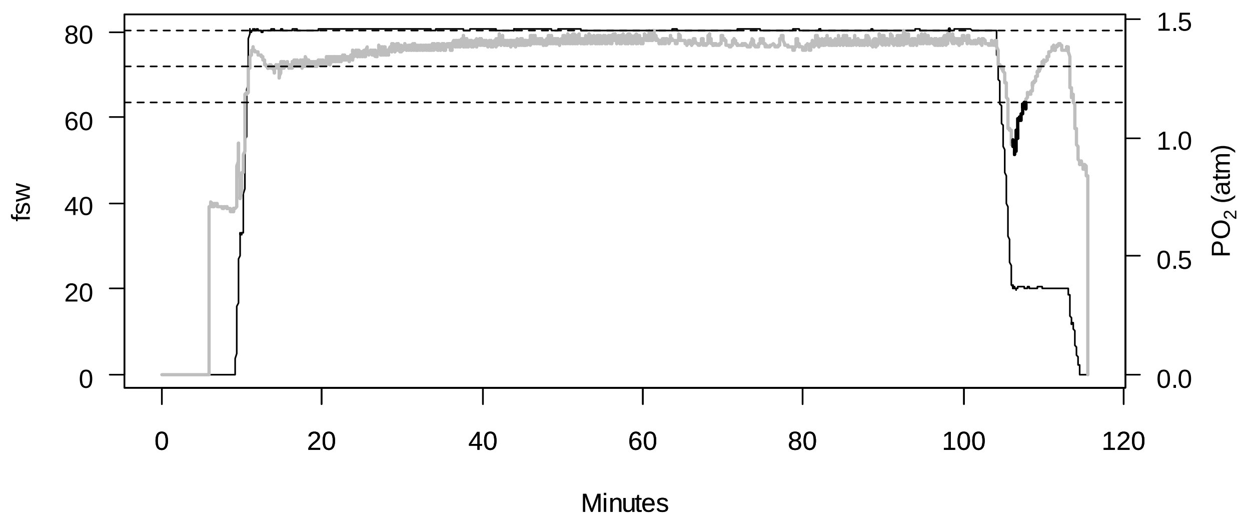

Figure 5. The increase and plateau in inspired PO_2 (grey line) during a long bottom time (dive profile indicated by thin black line). Divers performed cycle ergometer work for most of the bottom time but rested for 20 min. The less frequent oxygen injection during rest is manifest on inspired PO_2 trace between approximately 60 and 80 min.

DIRECT COMPARISON BETWEEN MEGALODON AND MK 16 MOD 1

General PO_2 control was compared for six Megalodon He-O_2 dives to 300 fsw for 20 minutes bottom time and eight MK 16 MOD 1 He-O_2 dives[5] with the same depth and bottom time — and for 24 Megalodon N_2-O_2 dives to 130 fsw for 30 minutes bottom time and 35 MK 16 MOD 1 N_2-O_2 dives[6] with the same depth and bottom time. No significant difference was evident in TWA PO_2 post-overshoot between the Megalodon (mean 1.37; SD 0.010 atm) and the MK 16 MOD 1 (mean 1.41; SD 0.04, two-sided unpaired t-test; $p=0.05733$) during He-O_2 dives. Similarly, there was no significant difference in TWA PO_2 post-overshoot between the Megalodon (mean 1.39; SD 0.019 atm) and the MK 16 MOD 1 (mean 1.41; SD 0.037 atm, two-sided unpaired t-test; $p=0.1035$) for the N_2-O_2 dives. The TWA PO_2 of the entire dive for the N_2-O_2 dives was significantly lower in the Megalodon (1.36; SD 0.019 atm) than in the MK 16 MOD 1 (1.41; SD 0.138 atm, two-sided unpaired t-test; $p=0.037$). The TWA PO_2 of the entire dive for the He-O_2 dives was not significantly different between the Megalodon (1.36 SD 0.013) and the MK 16 MOD 1 (1.35 SD 0.03, two-sided unpaired t-test; $p=0.43$).

Overshoot metrics were compared for the same Megalodon and MK 16 MOD 1 He-O_2 dives. The mean overshoot duration for the Megalodon dives (9.07; SD 1.25 min) was significantly shorter than for the MK 16 MOD 1 dives (13.41; SD 4.22 min, two-sided unpaired t-test; $p=0.02337$). The integral CNSTDE and maximum PO_2 were not significantly different between UBAs. Unfortunately, no MK 16 MOD 1 N_2-O_2 dives with reliable measures of PO_2 overshoot are comparable to the present Megalodon dives:

the MK 16 MOD 1 N_2-O_2 dives conducted to the same depths as those in the present study used an oxygen measuring method that inadequately accounted for the transit times of gas from the sample site to the paramagnetic oxygen analyzer,[6] and results from those dives therefore cannot be used to characterize rapidly changing PO_2.

Undershoot was also compared for 24 Megalodon ascents from 130 fsw to a 20 fsw first decompression stop and for 12 MK 16 MOD 1 ascents from 120 fsw to a 20 fsw first decompression stop.[6] These MK 16 MOD 1 dives are the most similar N_2-O_2 dives available, using a method that can characterize rapidly changing PO_2. Despite the Megalodon's larger ascent to the 20 fsw first stop, it had a significantly shorter undershoot (mean 1.28; SD 0.41 min) than did the MK 16 MOD 1 (mean 2.95; SD 0.39 min, two-sided unpaired t-test; $p<0.0001$). Also, the minimum PO_2 during ascent was significantly higher for the Megalodon (mean 0.92; SD 0.02 atm) than for the MK 16 MOD 1 (mean 0.77; SD 0.09 atm, two-sided unpaired t-test; $p<0.001$).

QUALITATIVE MEGALODON PERFORMANCE

Fifty-nine surveys were received in response to the 99 UBA-dives conducted in the OSF and 28 training dives completed under NEDU Short Form Test Plan 10-24.[3] The results are shown in Table 10.

The survey also provided a section for comments, which were varied and not tabulated. However, a few complaints were repeated frequently. The lengths of the inhalation and exhalation hoses were too short and thus restricted head movements. Manual addition of diluent during descent was required to maintain breathing loop volume. The counterlungs overinflated during ascent. Comments that were fewer in frequency included complaints about the general bulk of the UBA (the bulk of its handsets, in particular), the mouthpiece and its bulk, and the complexity of dressing in and out of the Megalodon. The Megalodon's breathability depended highly on the positioning of the counterlungs: one diver commented that with the counterlungs snug to the chest and flush, the diluent addition valve adequately maintained loop volume on descent. Most divers stated that they became increasingly comfortable with the Megalodon as they accumulated more hours diving it.

As briefly described in the **Introduction** and **Diving Procedures** sections, the Megalodon requires manual transition between available PO_2 set points (0.4, 0.7, 1.0, 1.1, 1.2, 1.3, and 1.4 atm). To use a decompression procedure authorized by the U.S. Navy, the Megalodon was dived according to the MK 16 MOD 1 decompression tables. These tables are calculated to assume a UBA having a PO_2 of 0.7 atm until its first descent deeper than 33 fsw; then it transitions to a PO_2 of 1.3 atm until it makes an ascent shallower than 12 fsw at which point it transitions back to 0.7 atm. These are switches that the MK 16 MOD 1 makes automatically as it passes through these depths, and it is essential that these set point transitions be made at the correct depths if divers using the Megalodon are to decompress according to MK 16 MOD 1 decompression tables. To ensure an orderly set point transition in order to test oxygen control, divers were verbally directed through the transition procedure. Divers and diving supervisors remained vigilant by providing detailed dive briefs and repetitive training. Despite these

precautions, one diver incorrectly transitioned his UBA to manual mode, a mistake requiring the dive to be aborted.

Table 10. Qualitative survey data

Question	Good (n=)	Fair (n=)	Poor (n=)	Unacceptable (n=)	N/A (n=)	Blank (n=)
The ease of dress for this rig was:	41	18	0	0	0	0
The ease of undress for this rig was:	43	16	0	0	0	0
The weight of this rig relative to other USN UBAs	36	18	3	1	1	0
The bulk of this rig relative to other USN UBAs	28	27	2	1	1	0
The ability to make adjustments to the rig was	34	18	2	0	0	5
Access to straps was	35	23	0	0	0	1
Access to valves was	43	16	0	0	0	0
Access to gauges was	52	6	0	0	0	1
Topside, ability to move your head	13	31	14	1	0	1
Topside, ability to move your legs	45	13	0	0	0	1
Topside, ability to move arms	55	4	0	0	0	0
Underwater, ability to move your head	12	34	13	0	0	0
Underwater, ability to move arms	52	7	0	0	0	0
Underwater, ability to move your legs	58	1	0	0	0	0
Your ability to adjust and maintain trim in the water	23	25	7	1	3	0
Comfort of the mouthpiece	10	30	13	3	3	0
Breathing resistance	24	27	4	2	0	2
Ease with which a flooded mouthpiece was cleared	40	11	0	0	8	0
Ease with which purge procedures were performed	30	21	1	0	7	0
Performance of this UBA in an operational environment	32	16	6	0	5	0

MAINTENANCE RECORDS OF MEGALODON DURING TESTING

Five Megalodon UBAs, designated “Meg 1” through “Meg 5,” were used during testing. Maintenance records that included pre- and postdive setup information, as well as any maintenance issues that were encountered, were completed throughout testing. Few problems occurred; most entailed routine maintenance. Table 11 presents log summaries.

Table 11. Maintenance on Megalodon UBAs during manned testing

Megalodon UBA	Record of Maintenance
Meg-1	25FEB10 – snap spring on head unit adjusted 15APR10 – Head Unit Replaced
Meg-2	25FEB10 – snap spring on head unit adjusted 14APR10 – replaced head unit 23AUG10 – rework head unit
Meg-3	25FEB10 – snap spring on head unit adjusted 19MAY10 – change diluent dump valve retaining ring to metal 18AUG10 – small leak on primary display – humidity 19AUG10 – primary display reassembled
Meg-4	Routine Maintenance only (change batteries, O_2 sensors)
Meg-5	Routine Maintenance Only

DISCUSSION

The Megalodon performed well against the performance specification and easily passed testing: its overall failure rate of 5% (95% confidence limits: 1,14%) was much less than the 15% reject criterion. This 15% maximum failure rate was chosen on the basis of previous performance of the MK 16 MOD 1, the only comparable UBA used by the U.S. Navy. The Megalodon's PO_2 control metrics and those of the MK 16 MOD 1 are comparable, with the only differences being in the Megalodon's shorter durations of overshoot upon descent and its PO_2s being closer to set point during ascent than those of the MK 16 MOD 1.

Following overshoot, PO_2 tended to drift high and plateau above 1.3 atm, but it generally remained within an acceptable control band (1.15–1.45 atm). The cause of this drift is unknown but is thought to be related to oxygen sensors. As a result, other experiments were performed to further characterize both the K-1D sensors used to acquire experimental data and the R-22 sensors that are part of the Megalodon's PO_2 control loop (see Appendix C). The most likely explanation is that this PO_2 drift is real — and related to a decrease in the R-22 voltage signal in the presence of warm, humid breathing gas. Nevertheless the Megalodon easily passed all criteria for oxygen control in manned testing and it compared favorably to the MK 16 MOD.

High PO_2 was also observed during un-unmanned testing of the Megalodon, but only in 28 °F water where PO_2 reached as high as 1.45 atm.[1] If the Megalodon is to be used in freezing conditions, thermal insulation of the R-22 sensors to improve oxygen control may be warranted, as proposed on the basis of these unmanned test results[1] (see Appendix C).

In addition to oxygen control, the Megalodon performed well in its subjective evaluation from divers. Several questions were raised with respect to hands-off operation of the UBA. Manual addition of diluent was needed to maintain loop volume during descent at a target rate of 60 fsw/min. This need may be ameliorated as divers accumulate more hours using the UBA and become familiar with positioning the counterlung that incorporates the automatic diluent add valve. The manual oxygen set point transition procedure worked well when divers were under verbal direction from the OSF control room, as only one diver failed to transition his UBA. We are unable to comment on whether the requirement to manually transition the oxygen set point will be operationally problematic, when free-swimming divers will not be under direct supervision. It seems likely that during ascents and descents divers will have to give more attention to monitoring and interacting with the Megalodon than they do with the MK 16 MOD 1. These are issues that will need to be addressed during training and familiarization with the Megalodon.

CONCLUSIONS

- The Megalodon passed the predefined acceptance criteria for oxygen control, when tested at 80 °F water temperature to maximum depths of 190 fsw with N_2-O_2 diluent and 300 fsw with He-O_2 diluent.

- The Megalodon performed adequately in controlling PO_2 on repetitive dives, whether the primary electronics were left on or turned off throughout the surface interval.

- The Megalodon's oxygen set point control compares favorably with that of the MK 16 MOD 1.

- The Megalodon presents some unfavorable human-factor problems, but these can be overcome with adequate user training.

RECOMMENDATIONS

- The Megalodon can be used with N_2-O_2 diluent to a maximum depth of 150 fsw and with He-O_2 diluent to a maximum depth of 300 fsw.

- Extensive training and familiarization with the Megalodon will be required for it to be safely operated.

- The Megalodon can be used in accordance with MK 16 MOD 1 decompression tables, but diver vigilance is required to ensure timely and correct PO_2 set point transitions.

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APPENDIX A: DIVE PROFILES

Nitrogen-Oxygen Diluent Dive Profiles

Depth	Bottom Time	Decompression Stops (fsw) Stop times (min)				Total Ascent Time
		50	40	30	20	
80	95				7	9:40
*120	60			4	31	38:40
130	30				10	14:20
150	25				13	18:00
150	30				22	27:00
190	25	2	4	4	24	39:20

* denotes Part II dive profile

Helium-Oxygen Dive Profiles

Depth	Bottom Time	Decompression Stops (fsw) Stop times (min)										Total Ascent Time
		110	100	90	80	70	60	50	40	30	20	
*120	50									4	43	50:40
220	25					7	3	3	2	8	65	93:40
300	20	7	3	2	3	2	4	6	12	12	96	154

* denotes Part II dive profile

APPENDIX B: INDIVIDUAL DIVE PO_2 EVENTS

profile	Depth (max)	Desc. rate	Asc rate	BT	TTD	Dive PO_2 (max)	OS dur	OS PO_2 (TWA)	sum CNSTDE	BT PO_2 (TWA)	postOS PO_2 (TWA)	Dive PO_2 (TWA)	Dive PO_2 (min)	Asc PO_2 (min)	Asc PO_2 (TWA)	US dur	1st stop dur	1st stop depth
100819_AM_D1	130.73	61.86	28.25	29.93	45.42	1.66	2.07	1.54	14.13	1.35	1.37	1.32	0.70	0.89	1.25	1.75	9.93	20.17
100819_AM_D2	130.73	61.86	28.25	29.93	45.42	1.70	4.00	1.55	29.79	1.37	1.37	1.34	0.71	0.91	1.28	0.90	9.93	20.17
100819_AM_D3	130.73	61.86	28.25	29.93	45.42	1.82	6.00	1.59	56.12	1.39	1.37	1.35	0.72	0.88	1.26	0.63	9.93	20.17
100819_AM_D4	130.73	61.86	28.25	29.93	45.42	1.70	5.13	1.58	47.25	1.40	1.39	1.36	0.74	0.90	1.29	1.20	9.93	20.17
100823_AM_D1	130.83	62.95	27.81	30.03	45.33	1.66	4.70	1.58	40.13	1.39	1.39	1.36	0.7	0.91	1.28	1.32	9.90	19.92
100823_AM_D2	130.83	62.95	27.81	30.03	45.33	1.71	5.47	1.60	57.24	1.39	1.38	1.36	0.69	0.91	1.30	0.75	9.90	19.92
100823_AM_D3	130.83	62.95	27.81	30.03	45.33	1.69	3.58	1.55	25.32	1.37	1.37	1.34	0.70	0.94	1.30	0.55	9.90	19.92
100823_AM_D4	130.83	62.95	27.81	30.03	45.33	1.69	3.32	1.58	29.34	1.39	1.39	1.36	0.71	0.95	1.31	0.75	9.90	19.92
100823_PM_D1	130.72	63.93	29.18	29.98	45.08	1.64	4.08	1.57	32.19	1.42	1.42	1.38	0.73	0.93	1.29	1.67	9.93	19.92
100823_PM_D2	130.72	63.93	29.18	29.98	45.08	1.61	2.88	1.51	15.35	1.38	1.39	1.34	0.72	0.90	1.26	1.82	9.93	19.92
100823_PM_D3	130.72	63.93	29.18	29.98	45.08	1.83	4.97	1.67	75.83	1.42	1.40	1.38	0.73	0.91	1.29	1.23	9.93	19.92
100823_PM_D4	130.72	63.93	29.18	29.98	45.08	1.73	2.8	1.58	26.86	1.41	1.42	1.37	0.73	0.93	1.30	1.55	9.93	19.92
100824_AM_D1	130.57	59.63	28.84	30.03	45.00	1.57	1.13	1.50	5.74	1.36	1.38	1.33	0.72	0.91	1.28	1.50	9.90	19.94
100824_AM_D2	130.57	59.63	28.84	30.03	45.00	1.63	2.18	1.56	16.60	1.35	1.36	1.32	0.61	0.89	1.27	1.52	9.90	19.94
100824_AM_D3	130.57	59.63	28.84	30.03	45.00	1.70	4.08	1.55	29.37	1.37	1.37	1.34	0.70	0.91	1.27	0.77	9.90	19.94
100824_AM_D4	130.57	59.63	28.84	30.03	45.00	1.65	4.00	1.54	26.86	1.36	1.36	1.34	0.68	0.93	1.29	0.55	9.90	19.94
100824_PM_D1	130.51	56.99	29.17	30.02	44.87	1.72	6.38	1.60	65.25	1.44	1.43	1.40	0.75	0.89	1.31	0.93	9.93	19.83
100824_PM_D2	130.51	56.99	29.17	30.02	44.87	1.78	3.5	1.61	38.95	1.42	1.42	1.39	0.74	0.97	1.32	1.37	9.93	19.83
100824_PM_D3	130.51	56.99	29.17	30.02	44.87	1.67	3.57	1.55	26.46	1.43	1.45	1.39	0.70	0.96	1.31	1.53	9.93	19.83
100824_PM_D4	130.51	56.99	29.17	30.02	44.87	1.71	4.68	1.59	44.06	1.43	1.43	1.38	0.74	0.94	1.29	1.38	9.93	19.83
100825_AM_D1	130.70	57.22	26.93	30.02	45.12	1.66	4.72	1.58	40.26	1.38	1.37	1.34	0.68	0.88	1.26	1.12	9.67	20.04
100825_AM_D2	130.70	57.22	26.93	30.02	45.12	1.81	5.20	1.66	78.43	1.42	1.40	1.38	0.71	0.93	1.31	0.78	9.67	20.04
100825_AM_D3	130.70	57.22	26.93	30.02	45.12	1.69	4.43	1.55	31.72	1.39	1.39	1.36	0.71	0.93	1.30	1.03	9.67	20.04
100825_AM_D4	130.70	57.22	26.93	30.02	45.12	1.77	5.73	1.64	75.86	1.40	1.36	1.36	0.72	0.91	1.27	1.03	9.67	20.04
100826_AM_D1	191.00	54.66	28.87	25.03	65.55	1.97	8.65	1.73	205.67	1.48	1.39	1.39	0.71	0.90	1.34	0.00	1.90	50.43
100826_AM_D2	191.00	54.66	28.87	25.03	65.55	1.99	7.05	1.72	160.87	1.46	1.40	1.39	0.68	0.91	1.35	0.00	1.90	50.43
100826_AM_D3	191.00	54.66	28.87	25.03	65.55	1.83	6.35	1.65	93.53	1.42	1.38	1.37	0.71	0.92	1.35	0.00	1.90	50.43
100826_AM_D4	191.00	54.66	28.87	25.03	65.55	2.01	8.37	1.73	196.97	1.48	1.39	1.40	0.72	0.93	1.36	0.00	1.90	50.43
100826_PM_D1	191.12	55.09	28.66	25.02	65.68	2.24	12.03	1.83	495.17	1.61	1.46	1.47	0.61	0.93	1.38	0.48	1.90	50.32
100826_PM_D2	191.12	55.09	28.66	25.02	65.68	2.05	11.57	1.76	318.00	1.58	1.46	1.47	0.76	0.95	1.40	0.00	1.90	50.32
100826_PM_D3	191.12	55.09	28.66	25.02	65.68	2.02	7.93	1.75	211.31	1.52	1.46	1.43	0.74	0.93	1.38	0.00	1.90	50.32
100826_PM_D4	191.12	55.09	28.66	25.02	65.68	2.14	8.75	1.79	287.17	1.55	1.45	1.44	0.73	1.18	1.37	0.00	1.90	50.32

profile	Depth (max)	Desc. rate	Asc rate	BT	TTD	Dive PO_2 (max)	OS dur	OS PO_2 (TWA)	sum CNSTDE	BT PO_2 (TWA)	postOS PO_2 (TWA)	Dive PO_2 (TWA)	Dive PO_2 (min)	Asc PO_2 (min)	Asc PO_2 (TWA)	US dur	1^{st} stop dur	1^{st} stop depth
100830_AM_D1	191.30	54.64	29.36	24.57	64.78	1.98	7.50	1.76	206.64	1.47	1.38	1.40	0.72	0.95	1.35	0.00	1.93	50.74
100830_AM_D2	191.30	54.64	29.36	24.57	64.78	1.98	9.13	1.74	224.40	1.48	1.38	1.39	0.67	0.97	1.34	0.00	1.93	50.74
100830_AM_D3	191.30	54.64	29.36	24.57	64.78	2.00	7.53	1.73	182.92	1.46	1.39	1.40	0.7	0.97	1.36	0.00	1.93	50.74
100830_AM_D4	191.30	54.64	29.36	24.57	64.78	1.96	9.38	1.75	237.98	1.48	1.37	1.41	0.69	1.15	1.34	0.00	1.93	50.74
100831_AM_D1	151.21	54.52	28.72	24.53	43.62	1.88	6.87	1.60	75.57	1.41	1.36	1.35	0.7	0.89	1.27	1.32	12.92	20.37
100831_AM_D2	151.21	54.52	28.72	24.53	43.62	1.97	5.53	1.68	106.42	1.41	1.39	1.36	0.65	0.90	1.28	1.48	12.92	20.37
100831_AM_D3	151.21	54.52	28.72	24.53	43.62	1.81	5.55	1.60	59.75	1.38	1.35	1.34	0.65	0.89	1.28	1.13	12.92	20.37
100831_AM_D4	151.21	54.52	28.72	24.53	43.62	1.72	4.63	1.57	38.86	1.39	1.38	1.35	0.73	0.90	1.30	0.85	12.92	20.37
100831_PM_D1	151.07	55.92	28.53	24.53	43.65	1.79	4.87	1.65	69.98	1.44	1.42	1.38	0.74	0.92	1.31	1.23	12.92	20.33
100831_PM_D2	151.07	55.92	28.53	24.53	43.65	1.93	5.28	1.66	82.99	1.47	1.44	1.40	0.76	0.92	1.31	1.25	12.92	20.33
100831_PM_D3	151.07	55.92	28.53	24.53	43.65	1.82	6.23	1.66	94.63	1.47	1.44	1.40	0.76	0.89	1.30	1.52	12.92	20.33
100831_PM_D4	151.07	55.92	28.53	24.53	43.65	1.89	5.87	1.66	88.49	1.47	1.45	1.41	0.74	0.92	1.33	1.07	12.92	20.33
100901_AM_D1	80.81	61.21	28.68	94.92	105.33	1.46	NA	NA	NA	1.38	NA	1.37	0.7	0.90	1.23	1.73	6.93	20.29
100901_AM_D2	80.81	61.21	28.68	94.92	105.33	1.52	NA	NA	NA	1.40	NA	1.39	0.7	0.96	1.28	1	6.93	20.29
100901_AM_D3	80.81	61.21	28.68	94.92	105.33	1.48	NA	NA	NA	1.40	NA	1.38	0.72	0.93	1.25	1.48	6.93	20.29
100901_AM_D4	80.81	61.21	28.68	94.92	105.33	1.51	0.52	1.48	2.12	1.38	1.39	1.37	0.70	0.92	1.27	1.02	6.93	20.29
100907_H1_D1	221.31	55.96	28.68	24.62	119.55	1.86	6.62	1.62	84.51	1.40	1.36	1.36	NA	1.00	1.35	0.00	6.90	70.61
100907_H1_D2	221.31	55.96	28.68	24.62	119.55	1.92	7.37	1.65	107.54	1.39	1.33	1.34	NA	0.92	1.32	0.00	6.90	70.61
100907_H1_D3	221.31	55.96	28.68	24.62	119.55	1.92	7.25	1.66	113.15	1.41	1.36	1.37	NA	0.91	1.36	0.00	6.90	70.61
100908_H1_D1	221.71	57.71	28.78	24.57	119.07	1.65	4.23	1.49	23.72	1.35	1.36	1.35	0.68	0.94	1.35	0.00	6.90	70.48
100908_H1_D2	221.71	57.71	28.78	24.57	119.07	1.82	5.53	1.65	76.31	1.38	1.35	1.34	0.65	0.96	1.33	0.00	6.90	70.48
100908_H1_D3	221.71	57.71	28.78	24.57	119.07	1.65	5.30	1.55	37.72	1.38	1.37	1.36	0.67	0.96	1.36	0.00	6.90	70.48
100908_H1_D4	221.71	57.71	28.78	24.57	119.07	1.75	6.23	1.60	67.48	1.38	1.34	1.34	0.72	0.95	1.34	0.00	6.90	70.48
100909_H2_D1	300.91	53.10	29.44	19.57	174.45	1.98	9.87	1.71	203.44	1.49	1.36	1.36	0.67	0.90	1.34	0.00	6.90	110.57
100909_H2_D2	300.91	53.10	29.44	19.57	174.45	1.84	8.55	1.66	129.48	1.45	1.35	1.34	0.68	0.89	1.33	0.00	6.90	110.57
100909_H2_D3	300.91	53.10	29.44	19.57	174.45	2.01	8.50	1.73	196.39	1.48	1.38	1.38	0.69	0.94	1.37	0.00	6.90	110.57
100913_H2_D1	302.38	53.93	28.40	19.55	175.07	1.90	8.55	1.66	144.66	1.45	1.37	1.36	0.67	0.91	1.35	0.00	6.58	110.78
100913_H2_D2	302.38	53.93	28.40	19.55	175.07	2.07	11.2	1.76	312.52	1.56	1.37	1.37	0.70	0.92	1.34	0.00	6.58	110.78
100913_H2_D4	302.38	53.93	28.40	19.55	175.07	1.92	7.73	1.68	138.71	1.45	1.36	1.36	0.69	0.93	1.34	0.00	6.58	110.78

TTD: Total time dive; Dive PO_2 (max): maximum PO_2 during dive; OS dur: duration of overshoot; OS PO_2 (TWA): Time-weighted Average of PO_2 during overshoot; sum CNSTDE: integral of Central Nervous System Toxic Dose Excess; BT PO_2(TWA): Time-weighted Average of PO_2 during bottom time; postOS PO_2(TWA): Time-weighted Average of PO_2 post-overshoot; Dive PO_2(TWA): Time-weighted average of PO_2 during entire dive; Dive PO_2(min): minimum PO_2 during dive; Asc PO_2(min): minimum PO_2 during ascent; Asc PO_2(TWA): Time-weighted average of PO_2 during ascent; USdur: duration of the undershoot; 1^{st}stop dur: duration of the 1^{st} decompression stop; 1^{st} stop depth: depth of the 1^{st} decompression stop

APPENDIX C: CHARACTERISTICS OF THE K-1D AND R-22 OXYGEN SENSORS

K-1D SENSORS

Inspired PO_2 was measured with a K-1D oxygen sensor (Teledyne; Thousand Oaks, CA) housed in a sensor block (Figure C-1) located in line between the inspiration counterlung and the inspiration hose. The K-1D oxygen sensor is a microfuel cell in which oxygen is reduced and a voltage signal is produced in proportion to the PO_2. This voltage signal was amplified approximately fiftyfold with an amplifier integrated into the sensor housing. Each integrated amplifier's voltage output was shown to be linear over the range of expected K-1D sensor voltages.[1] Before each dive, a two-point calibration was performed by recording voltage while flushing each sensor assembly (microfuel cell, amplifier, and housing) with 100% nitrogen and 100% oxygen at 1 atm·abs. PO_2 during the dive was calculated with a linear relationship assumed between PO_2 and sensor voltage.

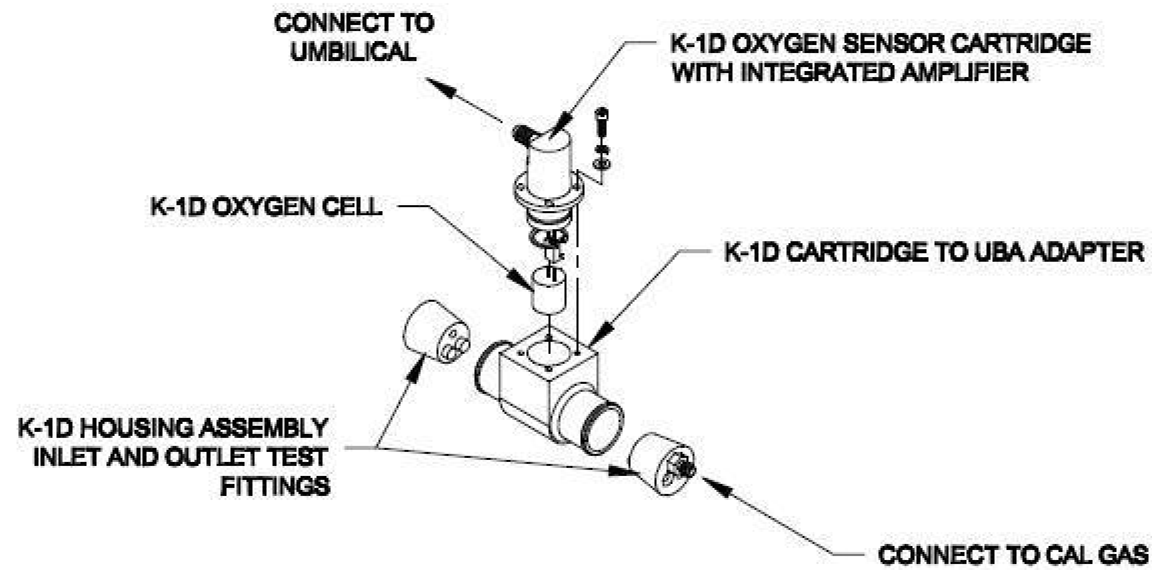

Figure C-1. Exploded view of sensor housing. Test fittings are used for calibration, whereas during diving the UBA hoses are connected at these locations.

Five K-1D oxygen sensors were used to measure inspired PO_2 in this dive series. The linearity of sensor response to PO_2 levels up to 3.5 atm was determined before and after the series. Sensors were exposed to air of 49.99% oxygen (balance nitrogen) at pressure from 1 atm·abs (0 fsw) to 6.99 atm·abs (198 fsw) in steps of 0.5 atm (16.5 fsw) or 1.0 atm (33 fsw) in a hyperbaric chamber (see, for instance, Figure C-2), while voltage was measured with a calibrated volt-ohm meter fitted with a 100-kΩ load

resistor. Raw (unamplified) sensor voltage, chamber pressure (fsw), and chamber temperature (°F) — all resolved to four decimal places — were acquired at 10 Hz.

Curves were fit by least squares regression to the chamber PO_2 (oxygen fraction x atm·abs) and sensor voltage. To minimize the influence of sensor response time (specified as <10 s to 90% final response), travel times to — and the first 10 s at — each pressure step were not included in these fits.

For each K-1D oxygen sensor, a quadratic of the form

$$V = a \times \left(PO_2\right)^2 + b \times PO_2 + c \qquad \text{(C-1)}$$

used in previous evaluation of K-1D sensors[2] fit the data well. However, the curvature parameter a, although significant, was small (around -1×10^{-4}), and a straight line,

$$V = b \times PO_2 + c\,, \qquad \text{(C-2)}$$

fit the data well with R^2 of at least 0.9998 for all sensors.

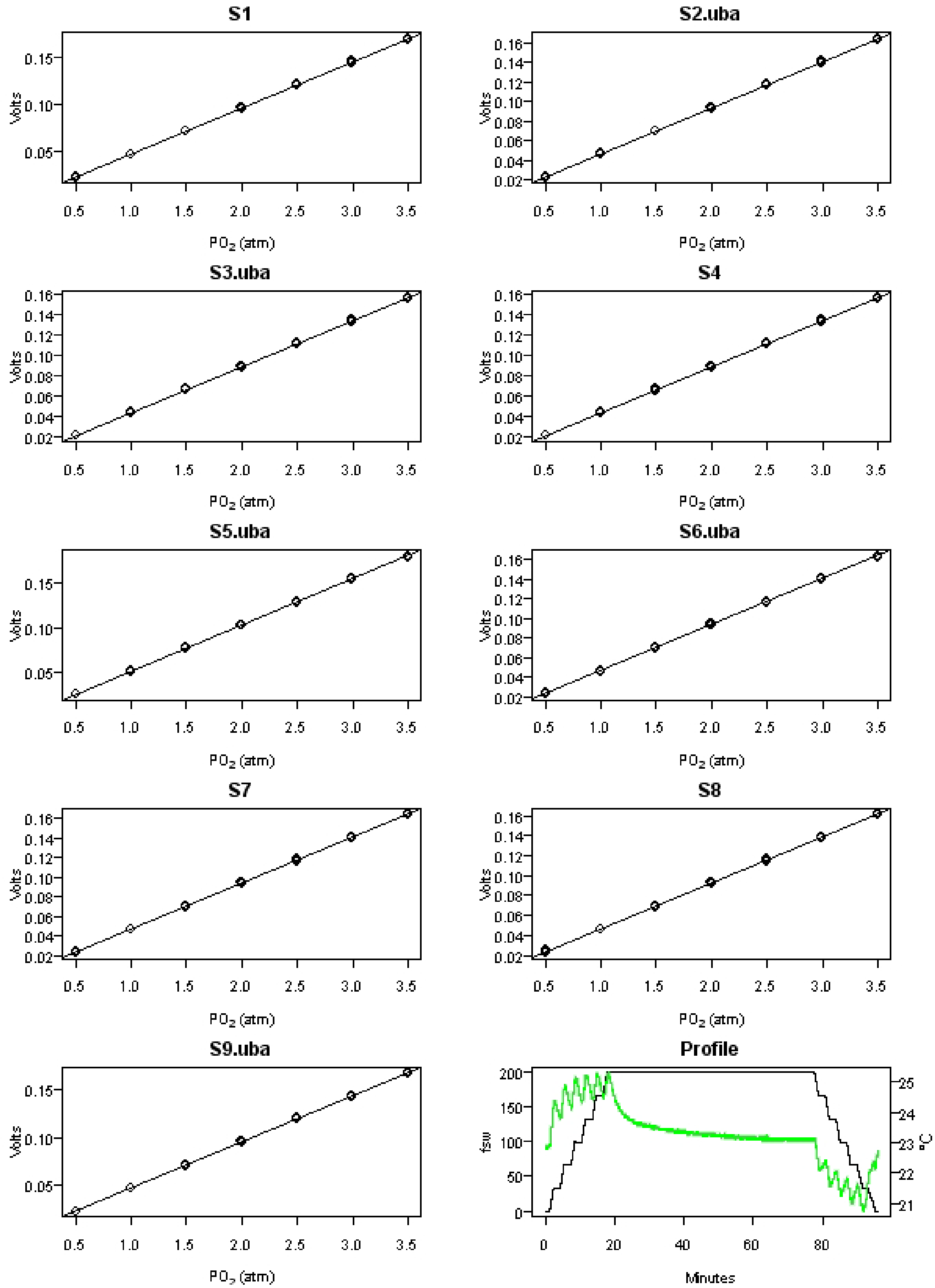

Figure C-2. Fit of straight lines to voltage output (circles) of K-1D sensors at various PO_2s obtained during compression and decompression in a 49.99% oxygen atmosphere. The lowest right panel shows the pressure (thin black line) and temperature (green line) profile.

Figure C-2 shows the fit of straight lines to the voltage signals from the five K-1D sensors used in the dive series (identified with the extension ".uba") — as well as from four additional sensors obtained at the same time but not used in the dive series. Note that the voltage response of these sensors is remarkably linear up to at least 3.5 atm PO_2, well above the maximum inspired PO_2 (2.24 atm) recorded in the dive series. Therefore, PO_2 calculated as a linear function of voltage and using the daily two-point sensor calibration required no additional correction.

Table C-1 gives the parameters *b* and *c* for calibration runs (49.99% oxygen, balance nitrogen) before and after the dive series for the five K-1D sensors used. No significant difference (two-sided paired t-test, df = 4, p>0.10) in parameters *b* and *c* resulted when they were tested under the same environmental conditions before and after the series.

Table C-1. Parameters of linear fit to K-1D data before and after the dive series under dry room temperature and hot, humid conditions

	Before		After		Hot, humid	
	c (intercept)	*b* (slope)	*c* (intercept)	*b* (slope)	*c* (intercept)	*b* (slope)
S2.uba	–0.0009	0.0450	–0.0004	0.0470	–0.0006	0.0476
S3.uba	0.0025	0.0495	–0.0004	0.0448	–0.0005	0.0448
S5.uba	0.0017	0.0501	–0.0008	0.0518	–0.0009	0.0525
S6.uba	0.0028	0.0457	–0.0004	0.0470	–0.0006	0.0476
S9.uba	–0.0004	0.0487	–0.0003	0.0481	–0.0003	0.0484

The accuracy of the K-1D oxygen sensors was questioned in response to the observation that measured inspired PO_2 in the Megalodon was generally higher than the 1.3 atm set point. Likely sources of inaccuracy in microfuel cell oxygen sensors inside a closed-circuit UBA's breathing circuit are humidity and heat, both of which are introduced in the diver's lungs and in the CO_2 absorbent reaction. Neither breathing gas temperature nor humidity was measured in this dive series.

In a microfuel cell, oxygen from the sample gas diffuses across a sensing membrane and a thin layer of electrolyte (typically KOH) is then reduced at a gold-plated cathode bathed in the electrolyte. Current between the cathode and lead anode is proportional to the rate of oxygen diffusion to the cathode and is therefore proportional to the PO_2 at the sensing membrane. Sensor output is the voltage across a resistor connecting the cathode and anode. Water condensing from humid gas onto the sensing membrane could modify the diffusion path for oxygen and result in a deceased sensor signal. Such condensation during diving was thought to decrease signals from Teledyne R10-DS microfuel cell oxygen sensors previously used to measure inspired PO_2 at NEDU.[3] An increase in gas sample temperature increases the rate of oxygen diffusion to the cathode and can increase a sensor signal. K-1D microfuel cells are constructed with a negative coefficient thermistor connecting the cathode and anode, so that the voltage signal is decreased to compensate for increased rate of oxygen diffusion with an increased temperature.

Several observations implicated inadequate temperature compensation in microfuel cells in the high measures of inspired PO_2 during the dive series. First, for the initial 16 UBA-dives of this series the K-1D sensor assembly was located between the CO_2 absorbent canister and the inhalation counterlung; subsequently it was moved downstream from the inspiration counterlung, nearer the diver's mouth, to make its readings more representative of inspired gas. PO_2s recorded in that initial position were higher than in the latter position, and, since gas heated during the CO_2 absorbent reaction may have cooled in passing through the inspiration counterlung and hoses exposed to 28 °C water, gas temperatures may have been different at the two locations. Second, four of the initial 16 UBA-dives (with the K-1D sensor assembly upstream of the inspiration counterlung) were conducted with divers at rest throughout and the PO_2 was somewhat lower than in comparable dives during which divers worked, a result possibly related to lower metabolic CO_2 production and lower heat production in the CO_2 absorbent reaction with divers at rest. Finally, during unmanned Megalodon testing,[4] differences in inspired PO_2 regulation around a 1.3 atm set point depended on the water temperature and on whether CO_2 was injected into the simulated expired gas stream — and therefore on whether a heat-producing CO_2 absorbent reaction had occurred.

As an initial test, a single K-1D oxygen sensor assembly was calibrated with dry, room temperature 100% nitrogen and 100% oxygen and then was exposed to dry, heated 100% oxygen for one hour. Although no change in actual PO_2 resulted, K-1D voltage output increased with temperature. Figure C-3 shows the increase in PO_2 calculated from the room temperature calibration when the sensor membrane is exposed to 100% oxygen at approximately 30 °C. A greater increase in K-1D sensor voltage was observed when gas was heated to 35 °C (Figure C-3, right panel). These increases are substantially greater than the K-1D specifications imply. The Megalodon's inspired breathing gas temperature was not measured in either unmanned or manned testing, but breathing gas leaving the MK 16 MOD 1 (another closed-circuit UBA) absorbent canister can be as high as 30 °C (W. A. Gerth, unpublished data).

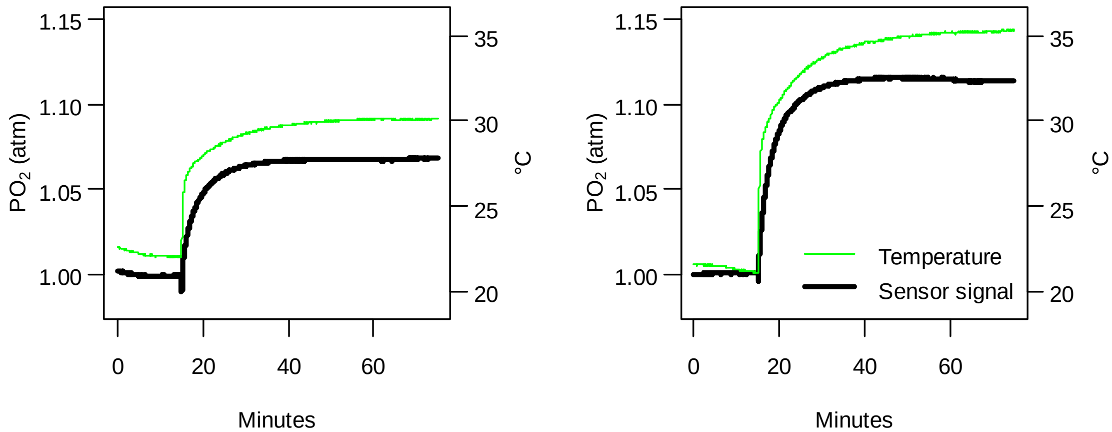

Figure C-3. Increase in the K-1D signal when the sensor is exposed to heated gas.

The K-1D sensors used in this dive series were again subjected to the same test of response linearity to PO_2s up to 3.5 atm, as described in pages C-1 through C-4, but this time with the hyperbaric chamber heated to ~30 °C and with the chamber floor covered in water to produce a humid atmosphere. Under these conditions, water was visibly condensed on the chamber's acrylic walls. The sensors were not submerged and were oriented with their sensing membranes in a vertical plane, so that condensed water would not pool on them. Figure C-4's lowest right panel shows the pressure and temperature profile of this chamber run. The other panels show the fit of straight lines to the voltage signals from the five K-1D sensors used and the four additional sensors not used in the series.

Even under the hot, humid conditions, the voltage response of these sensors is linear up to at least 3.5 atm PO_2. However, Table C-1 compares parameters b and c for calibration runs (49.99% oxygen, balance nitrogen) under both dry, room temperature and hot, humid conditions. The hot, humid conditions resulted in a significant ~1% increase in parameter b (slope) in comparison to dry room temperature chamber runs (two-sided paired t-test, $t = -6.3156$, $df = 8$, $p=0.0002$) after the dive series. This temperature compensation more closely matches the published K-1D specifications than do results from the initial temperature test.

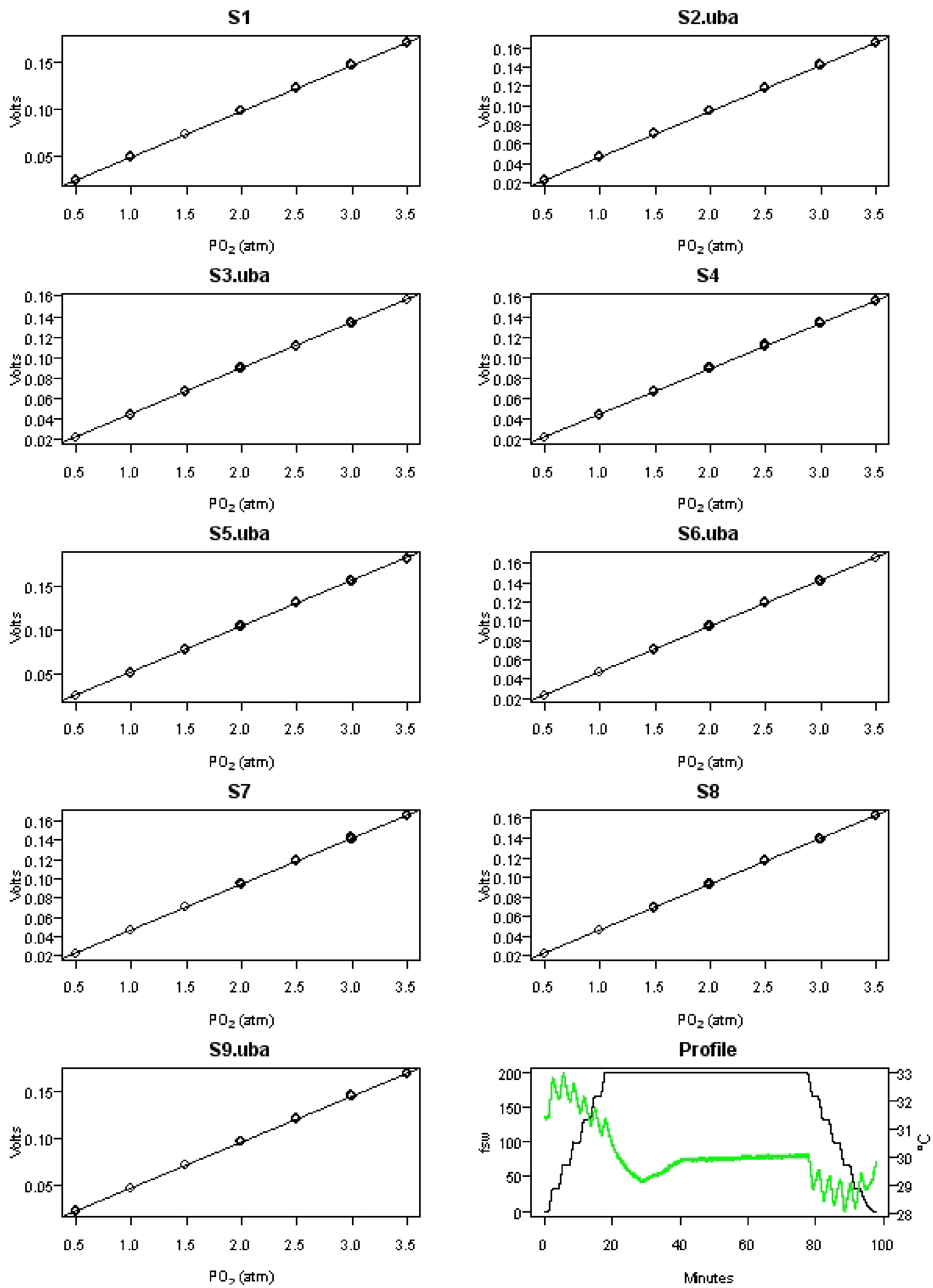

Figure C-4. Fit of straight lines to voltage output (circles) of K-1D sensors at various PO_2s obtained in a hot, humid 49.99% oxygen atmosphere. The lowest right panel shows the pressure (thin black line) and temperature (green line) profile.

These K-1D sensors exposed to 30 °C gas with a real PO_2 ($PO_{2.real}$) of 1.3 atm under hot, humid conditions would produce a voltage (V_{hot}) that would be interpreted as an apparent PO_2 ($PO_{2.app}$) of 1.31 atm on the basis of calibration at room temperature, according to

$$V_{hot} = PO_{2.real} \times b_{hot} + c_{hot} \text{ and} \tag{C-3}$$

$$PO_{2.app} = \left(V_{hot} - c_{rt}\right)/b_{rt} \;, \tag{C-4}$$

where c_{rt} and b_{rt} are calibration parameters measured at room temperature, and c_{hot} and b_{hot} are parameters of the sensor response at 30 °C.

Several explanations are possible for the much larger increase in $PO_{2.app}$ with a shift from room temperature calibration gas to 30 °C test gas in the initial test of the single K-1D sensor assembly (Figure C-3) than that increase seen when all sensors were tested in the hyperbaric chamber. First, this single sensor assembly may have behaved uncharacteristically. Second, the amplifier may have a positive temperature coefficient that adds to that of the microfuel cell. Third, the K-1D sensor temperature compensation may have been hindered by the sensor housing: although the sensing membrane is exposed to the flow of breathing gas, the body of the sensor, including presumably the temperature-compensating thermistor, is encased in the housing. Although the body of the sensor is in communication with the breathing circuit gas, they are not directly in the flow and may remain closer to the environmental temperature than to the test gas temperature. The bench test illustrated in Figure C-3 was conducted at room temperature (22 °C), so any temperature mismatch between the sensing membrane and the body of the sensor may have been greater than would have occurred during the dive series, when the sensor assembly was immersed in 28 °C water.

R-22 SENSORS

The Teledyne R-22 oxygen sensors in the Megalodon oxygen control system — microfuel cells located inside the breathing loop and exposed to hot, humid gas — may also be influenced by temperature changes and gas humidity during diving. Six R-22 sensors were subjected to the same test of response linearity to PO_2s up to 3.5 atm that the K-1D sensors received. Three of these R-22s were used sensors taken from Megalodon UBAs tested in the dive series, and three sensors were new. Figures C-5 and C-6 show the fit of straight lines to the raw data for the six R-22 sensors under dry room temperature and under hot, humid conditions, respectively. Under both conditions, the voltage responses of these sensors are linear up to at least 3.5 atm PO_2.

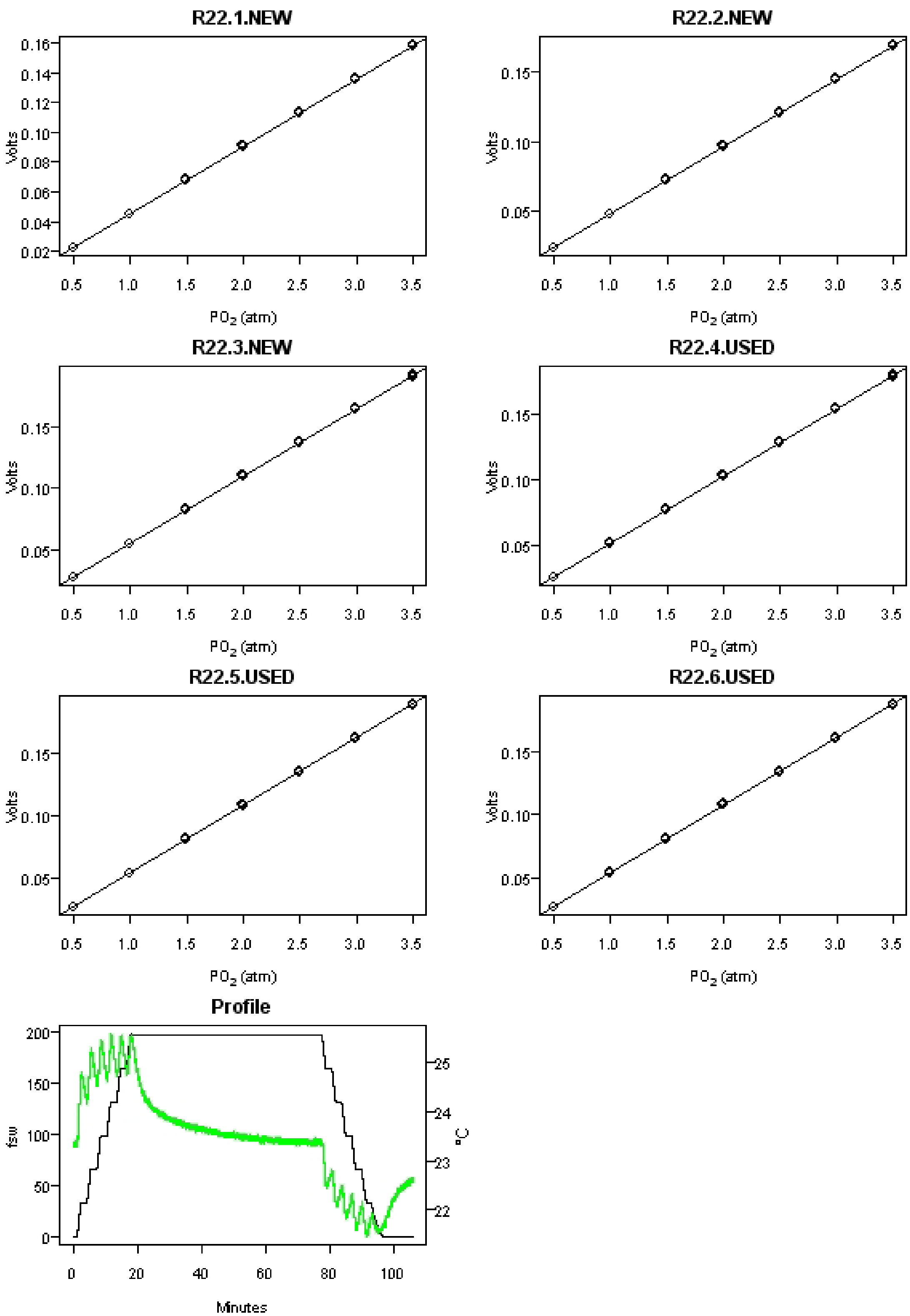

Figure C-5. Fit of straight lines to voltage output (circles) of R-22 sensors at various PO_2s in a dry, room temperature 49.99% oxygen atmosphere. The lowest panel shows the pressure (thin black line) and temperature (green line) profile.

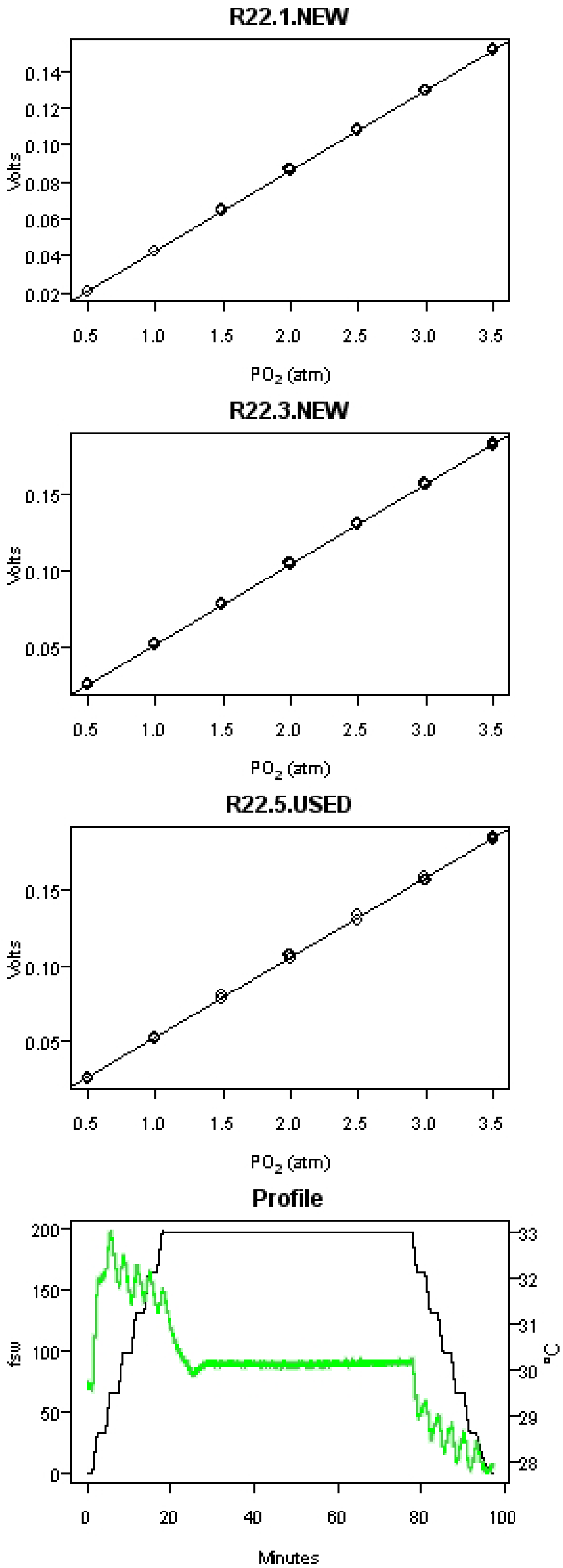

Figure C-6. Fit of straight lines to voltage output (circles) of R-22 sensors at various PO_2s in a hot, humid 49.99% oxygen atmosphere. The lowest panel shows the pressure (thin black line) and temperature (green line) profile.

Table C-2. Parameters of linear fit to R-22 data under dry, room temperature and hot, humid conditions

	Room temp, dry		Hot, humid	
	c (intercept)	b (slope)	c (intercept)	b (slope)
R22.1.NEW	0.0002	0.0452	–0.0003	0.0433
R22.2.NEW	0.0001	0.0483	–0.0005	0.0464
R22.3.NEW	0.0004	0.0549	–0.0005	0.0525
R22.4.USED	0.0006	0.0512	0.0003	0.0486
R22.5.USED	0.0003	0.0541	0.0003	0.0524
R22.6.USED	0.0004	0.0534	0.0003	0.0514

Table C-2 compares the parameters b and c for calibration runs (49.99% oxygen, balance nitrogen) under dry room temperature conditions and humid, hot conditions. There was a substantial (~5%) decrease in parameter b (slope) for the hot, humid data compared to the dry room temperature data (two-sided paired t-test, $t = 15.74$, $df = 5$, $p=0.0024$). In other words, the R-22 sensors output a lower voltage under hot, humid conditions than dry, room temperature conditions. As a result, a UBA calibrated at room temperature may maintain a real PO_2 higher than the set point once the gas in the breathing loop becomes hot and humid. The UBA control loop regulates sensor voltage, not PO_2 per se, by adding oxygen if the sensor voltage drops below that associated with the chosen PO_2 set point. If a control loop is calibrated at room temperature but the sensor — under hot, humid conditions in the breathing loop during diving — outputs a lower voltage than at calibration, the UBA must maintain the PO_2 higher than the PO_2 set point to keep the sensor at the voltage set point. For the R-22 sensors to output a voltage (V_{set}) interpreted as a PO_2 of 1.3 atm ($PO_{2.set}$) on the basis of a room temperature calibration, the actual PO_2 ($PO_{2.real}$) of 30 °C humid gas would need to be 1.36 atm, according to the following calculations:

$$V_{set} = PO_{2.set} \times b_{rt} + c_{rt} \quad \text{and} \tag{C-5}$$

$$PO_{2.real} = (V_{set} - c_{hot}) / b_{hot} \, . \tag{C-6}$$

According to Equations (C-3) and (C-4), if a K-1D microfuel cell calibrated at dry room temperature were then to sense this real PO_2 of 1.36 atm at 30 °C, the apparent PO_2 would read 1.37 atm. It is probably coincidental that the mean time-weighted average inspired PO_2 from all the Megalodon test dives was 1.37 atm.

INFLUENCE ON TEST RESULTS

If temperature and humidity effects on microfuel cells were to any extent responsible for observed Megalodon inspired PO_2 being elevated above set point, both the K-1D and the R-22 sensors must have contributed. So any increase in measured PO_2 would be partly real (due to R-22 effects) and partly artifactual (due to K-1D effects). In the hyperbaric chamber tests of raw microfuel cell signals, the R-22 effect was greater than that of the K-1D for the same temperature increase, as detailed in the preceding

paragraph. On the other hand, the amplified signal increase with temperature in the single K-1D sensor assembly (Figure C-3) was of the same magnitude as the R-22 effect, suggesting that the difference in measured Megalodon PO_2 from the set point could be, in equal parts, a real effect and artifact. Two observations suggest that the R-22 (real elevated PO_2) effect dominated over the K-1D. First, the Megalodon control loop's R-22s are located inside the canister body and adjacent to the CO_2 absorbent bed, where they would probably be exposed to warmer gas than were the K-1D cells. Second, PO_2s recorded during the second dive on the day were substantially higher than during the first dive of the day. The K-1D sensors were thoroughly dried between the first and second dive of the day, but the UBAs were not dried, so the R-22 cells may have been more affected by moisture condensation than the K-1Ds were.

Irrespective of how much the elevated PO_2 was artifactual because of the K-1D sensors, the results of the certification testing remain valid. The Megalodon passed testing with an acceptable rate of UBA-dive failures, all due to high PO_2. At least two of these dives most likely would not have resulted in failure if the measured PO_2 were as little as 0.01 atm lower (the likely magnitude of the K-1D artifact) than it was, a change resulting in an even lower failure rate. Even if the measured PO_2 were as much 0.06 atm lower (the magnitude of the K1-D sensor assembly artifact illustrated in Figure C-3) than it was, none of the UBA-dives would have resulted in failures due to low PO_2.

COMPARISON WITH UNMANNED UBA TESTING

Unmanned testing of steady-state UBA inspired PO_2 regulation[4] was conducted in water temperatures of 105 °F (41 °C), 70 °F (21 °C), and 28 °F (−2 °C). Simulated expired gas was heated and humidified but generally did not contain CO_2, so no CO_2 absorbent reaction produced heat. Under these conditions the R-22 sensor temperatures probably approach that of the surrounding water, because the body of the UBA is aluminum and the R-22 sensors are not insulated. In 21 °C and 41 °C water, steady-state UBA inspired PO_2 was near the 1.3 atm set point (with means ranging from about 1.27 to 1.33 atm, depending on depth) and was not different between the two water temperatures. The similarity of results between the two water temperatures does not support a decrease in R-22 voltage because of increasing temperature and suggests that the reduced R-22 sensor voltage described on page C-11 may have resulted from humidity.

In −2 °C water, steady-state inspired PO_2 was greater than the 1.3 atm set point, with a mean value of 1.45 atm at 99 fsw (see Layton,[4] Table 40). When simulated expired gas contained CO_2 and a heat-producing CO_2 absorbent reaction therefore occurred, the mean steady-state PO_2 was 1.37 atm in −2 °C water (Layton[4], Table 40). These high PO_2s were interpreted as resulting from cold R-22 cells producing a reduced signal voltage compared to that during room temperature calibration. These results imply that near-freezing temperatures have an effect on R-22 signal opposite from that described at higher temperatures on page C-11 and again supports the notion that the reduced R-22 sensor voltage under hot, humid conditions described on page C-11 may have resulted from humidity rather than temperature. It should be noted that −2 °C is less than the manufacturer-specified minimum operating temperature of 0 °C (32 °F) for

Teledyne microfuel cell oxygen senosrs, including the R-22, because microfuel cells will not operate if the aqueous electrolyte is frozen.[5] Indeed, Megalodon performance at −2 °C during unmanned testing elicited the recommendation that insulation of the R-22 sensors from ambient temperature might be warranted.[4]

CONCLUSIONS AND RECOMMENDATIONS

With a linear voltage response to PO_2 of up to at least 3.5 atm and adequate temperature compensation, the K-1D oxygen sensors are well suited for measuring PO_2 in manned UBA evaluations. However, the full sensor assembly (K-1D sensor, housing, and amplifier) should be fully evaluated over a range of PO_2s and ambient temperatures and under both dry and humid conditions.

The R-22 oxygen sensors used in the Megalodon control loop have not been characterized at NEDU to the same extent as have sensors intended for use in the MK 16[6,7], but operate well at temperatures within the manufacturer-specified operating range (0–40 °C).

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